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**A SIMPLE AND ACCURATE TECHNIQUE  
FOR MONITORING CRACK GROWTH BEHAVIOR  
USING A WAVE FORM ANALYZER**

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## INTRODUCTION

When fatigue tests are performed with three-point bend specimens, crack-mouth opening displacement is the preferred method to monitor compliance changes of the specimen as the crack grows. Often, however, crack-mouth opening displacement is difficult or impossible to monitor due to notch geometry, such as a wide semi-circular notch. Therefore, to establish the compliance changes under these conditions, another method of monitoring is required. Under load control testing, as a crack begins to grow, the test specimen becomes more compliant requiring greater piston displacement in order to maintain a constant load level. Some difficulties exist with monitoring load-line displacement, including interference from fixture compliance and brinelling (which occurs when the loading pins plastically deform the specimen locally). When monitoring load-line displacement, the brinelling effect causes the piston to deviate from its mean position leading the investigator to erroneously believe that a crack has begun to extend further into the remaining ligament. This type of behavior is also commonly labeled piston float and is a major reason why crack-mouth opening displacement is monitored instead of load-line displacement in fatigue and fracture toughness testing.

This report describes a monitoring technique that effectively eliminates the effect of piston float and allows simple, consistent monitoring of crack growth behavior when fatigue testing or precracking three-point bend specimens. This method is not as accurate as using a clip gage to monitor crack-mouth opening displacement, but it does provide a simple, alternative method when clip gages are difficult or impossible to use.

## EXPERIMENTAL METHODS

The technique for monitoring crack growth behavior in this report was developed while cycling three-point bend specimens that contained a 6.35-mm semi-circular notch, as shown in Figure 1. The 84 specimens were cycled at an R-ratio of 0.1 with  $P_{max}$  values of 28.7 and 48.3 kN. The material investigated was ASTM A723 steel and the specimens had three different notch surface treatments: shot peened, harperized (which produces a compressive surface stress by plastically deforming a hole or notch using an offset cam), and as-machined.

As shown in Figure 1, the 6.35-mm semi-circular notch in the beam specimens combined with the surface treatments being investigated made it difficult and inadvisable to affix knife edges onto the specimens. Also shown in Figure 1 is a schematic representation of the servo-hydraulic piston motion during fatigue cycling of three-point bend specimens. Since standard servo-hydraulic testing systems, such as the Instron 1332 used in this investigation, are calibrated for tension testing, a downward piston motion is considered positive (since this downward motion would put a tensile specimen in tension), and an upward piston motion is considered negative. By examining the change between the maximum and minimum piston position,  $Y_{max}$  and  $Y_{min}$ , the investigator could approximate the amount of crack growth during fatigue cycling if the effects of brinelling were reduced or eliminated. To quantify the effects of notch surface treatment, the bend specimens were to be cycled until the change in load-line displacement during the test increased by 10 percent. By examining the number of cycles required to achieve this displacement change, a consistent measure of the notch surface treatment was expected. To determine how consistent this test method was, the specimens were heat tinted at 600°F in air for

one hour and the corresponding 'tinted zone' (fatigue crack length) measured at five locations across the crack front.

## EXPERIMENTAL RESULTS

### Simple Load-Line Displacement Monitoring

Initially, the specimens in this investigation were cycled in load-control, while the change in piston position was recorded at 1000-cycle intervals. This difference between maximum and minimum piston position is the load-line displacement change and was expected to be an indicator of the extent of fatigue crack growth. After the first 1000 cycles, the difference between the maximum and minimum piston position was recorded and multiplied by 110 percent. This allowed the technician to set a limit switch on the test machines' computer controller to the precise piston stroke position required to obtain a 10 percent increase in displacement change due to crack growth. Since the notch used in this investigation was extremely blunt, 6.35-mm radius, macro-scale crack growth was not expected for several thousand cycles. However, the maximum piston position  $Y_{max}$ , or the lowest point to which the piston travels, was slowly rising during the cycling process. At the same time, the minimum piston position  $Y_{min}$ , or the highest point to which the piston travels, was also rising. This behavior is commonly referred to as piston float and was assumed to be caused by a combination of the machine warming up and the loading pins plastically deforming into the specimen (the brinelling effect). It was hoped that this behavior would fade as the cycling continued and become negligible after 2000 to 3000 cycles. However, as shown in Figure 2 this effect did not fade, and in fact it became worse as the cycling progressed.

The important point to be made from Figure 2 is the fact that even though the maximum and minimum piston positions are moving, the change between them,  $\Delta$ , is remaining constant. Thus, no macro-scale crack growth occurs until  $\Delta$  increases. As mentioned earlier, however, a limit switch had been set to stop the fatigue cycling once 110 percent of the *initial* displacement change,  $\Delta_{init}$ , had occurred. This limit stroke level,  $Y_{lim}$ , is shown in Figure 2 and indicates the minimum position of the piston, which corresponds to the maximum crack-mouth opening displacement when the machine will automatically shut itself off. After ten specimens were tested by this method, the fatigue cracks were measured. Since the test machine was automatically shutting itself off at precisely 110 percent of the original displacement change, the measured fatigue cracks were expected to be approximately equal in length. Table 1, however, shows the range of fatigue crack lengths obtained along with the mean and standard deviation associated with the specimens using the criterion of 110 percent of the original displacement change. Notice also that the mean increase in displacement change ( $\Delta$  increase (%)) was 14.5 percent--well above the target of 10 percent. This is due to the lack of control the test operator has over adjusting the  $Y_{lim}$  to compensate for piston float.

**Table 1.  $\Delta$  Increase (%) and Crack Length Data For Ten Three-Point Fatigue Specimens Tested Using the Load-Line Limiting Method**

<b>Load-Line Monitoring</b>		
<b>Specimen</b>	<b><math>\Delta</math> Increase (%)</b>	<b>Crack Length (mm)</b>
1	16.44	10.6
2	15.07	10.5
3	2.74	9.6
4	4.11	9.7
5	29.82	11.4
6	47.71	12.3
7	8.72	10.1
8	0.46	9.4
9	13.7	10.7
10	6.39	10.2
<b>Mean</b>	<b>14.52</b>	<b>10.5</b>
<b>Std. Dev.</b>	<b>14.47</b>	<b>0.9</b>

### **Span/Mean Stroke Position Monitoring**

The wave form analyzer, which is typically used in place of an oscilloscope, digitizes the feedback signals from the test machines' controller and allows the user to obtain many different types of information from a specific test being performed. Another benefit that the wave form analyzer has over an add-on signal analyzer like the oscilloscope is that it allows limiting control over the piston actuator. This means that it can be programmed to stop a test when a certain limiting criterion is satisfied. One criterion is the span/mean level. The span is actually the amplitude of the sinusoidal wave form used when performing a standard fatigue test, or in other terms, the difference between maximum and minimum displacement. The mean level is the stroke level around which the piston is cycling. Since the span only changes when the difference between maximum and minimum displacement changes, it does not matter that the pins are plastically deforming into the specimen. The span will only change when the compliance of the specimen changes, i.e., when a crack begins to grow. The mean level, however, does change and this is an exact indication of how much the piston 'floats' during cycling. Figure 3 is a plot of mean level versus cycles using the same data as in Figure 2. Comparing Figure 3 with Figure 4, which is a plot of piston span versus cycles, it is easy to see that the mean level of the piston has no effect on the span of the piston. Therefore, the exact increase in displacement change that is required for testing can be set.



To examine the accuracy of this method, ten more specimens were fatigue cycled--this time to a target  $\Delta$  increase of 14 percent in order to attempt to match the crack lengths of the ten specimens listed in Table 1. Table 2 shows the improved accuracy of this method, which produces equal crack lengths and allows the operator to automatically stop the test when the desired increase in displacement change is reached. Table 2 shows that by using the span level feedback as the limit switch, with a target  $\Delta$  increase of 14 percent, the standard deviation is only 1.2 percent, which is significantly less than the 14 percent standard deviation attained by limiting the test based on monitoring the load-line displacement.

**Table 2.  $\Delta$  Increase (%) and Crack Length Data for Ten Three-Point Bend Fatigue Specimens Tested Using the More Accurate Span Limiting Method**

<b>Span Level Monitoring</b>		
<b>Specimen</b>	<b><math>\Delta</math> Increase (%)</b>	<b>Crack Length (mm)</b>
11	15.9	10.5
12	13.6	10.3
13	13.1	10.3
14	12.7	10.3
15	15.2	10.3
16	12.2	10.1
17	13.4	10.1
18	14.03	10.6
19	14.7	10.4
20	14.75	11.1
<b>Mean</b>	<b>13.96</b>	<b>10.4</b>
<b>Std. Dev.</b>	<b>1.17</b>	<b>0.3</b>



## **SUMMARY**

A simple technique for monitoring the change in compliance of a standard three-point bend specimen during fatigue testing has been developed. By monitoring the span of the piston stroke, the test operator can automatically stop any fatigue test at a prescribed increase in compliance. Unlike monitoring the load-line displacement directly, this method eliminates the effect of brinelling and any other type of piston float. Current applications include fatigue testing specimens with large notches and/or special surface treatments that make it impractical to monitor crack-mouth opening displacement with a clip gage. Other applications may be in monitoring the fatigue precracking of fracture toughness specimens. Once the operator knows the displacement change required to produce a certain length crack in the specimen, the wave form analyzer could be set to shut the machine off at precisely the correct moment. This would save time and dramatically increase the accuracy of the precrack length.

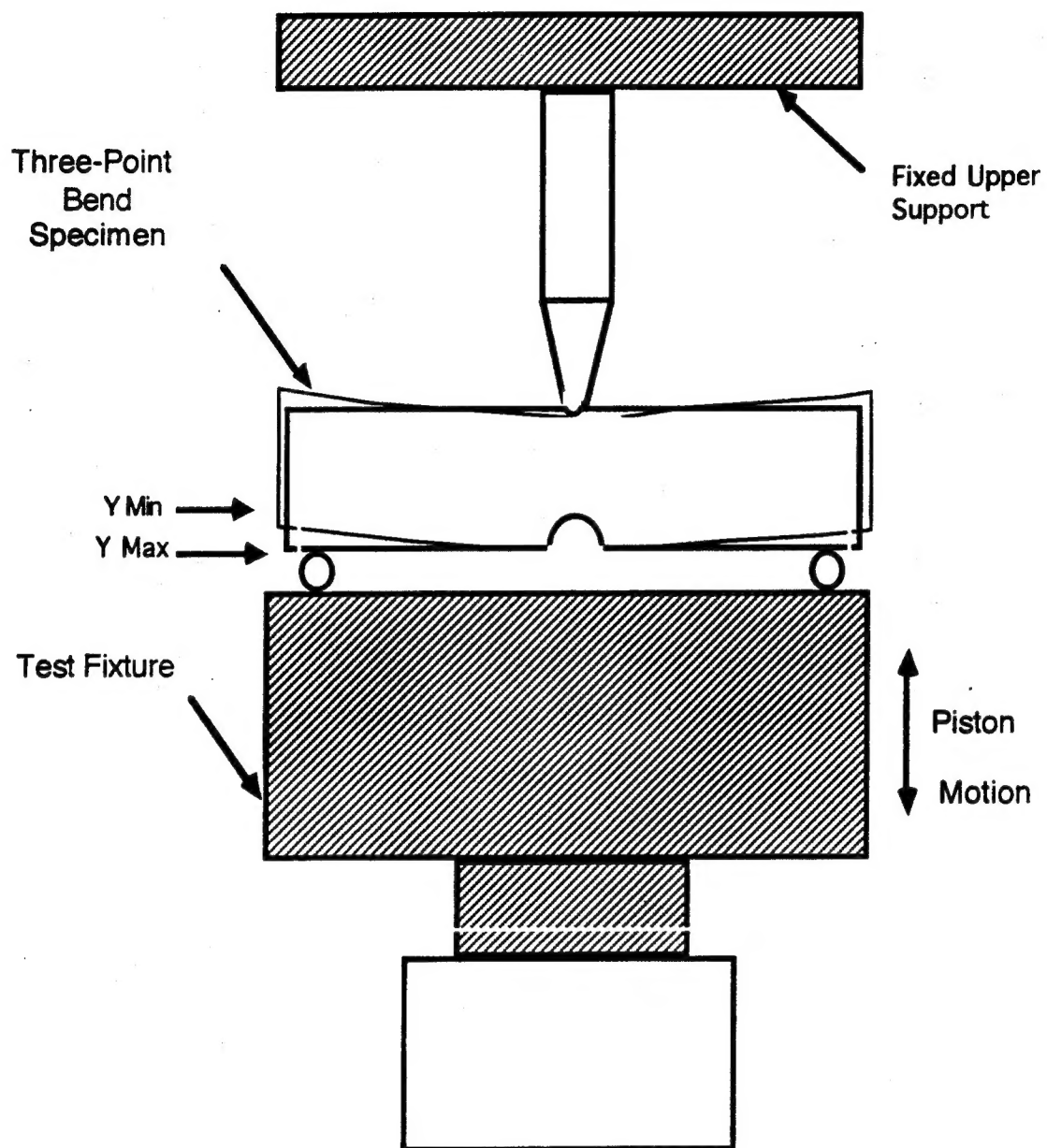


Figure 1. Schematic illustration of the test apparatus showing the bend specimen and the hydraulic piston motion with the corresponding maximum and minimum stroke positions.

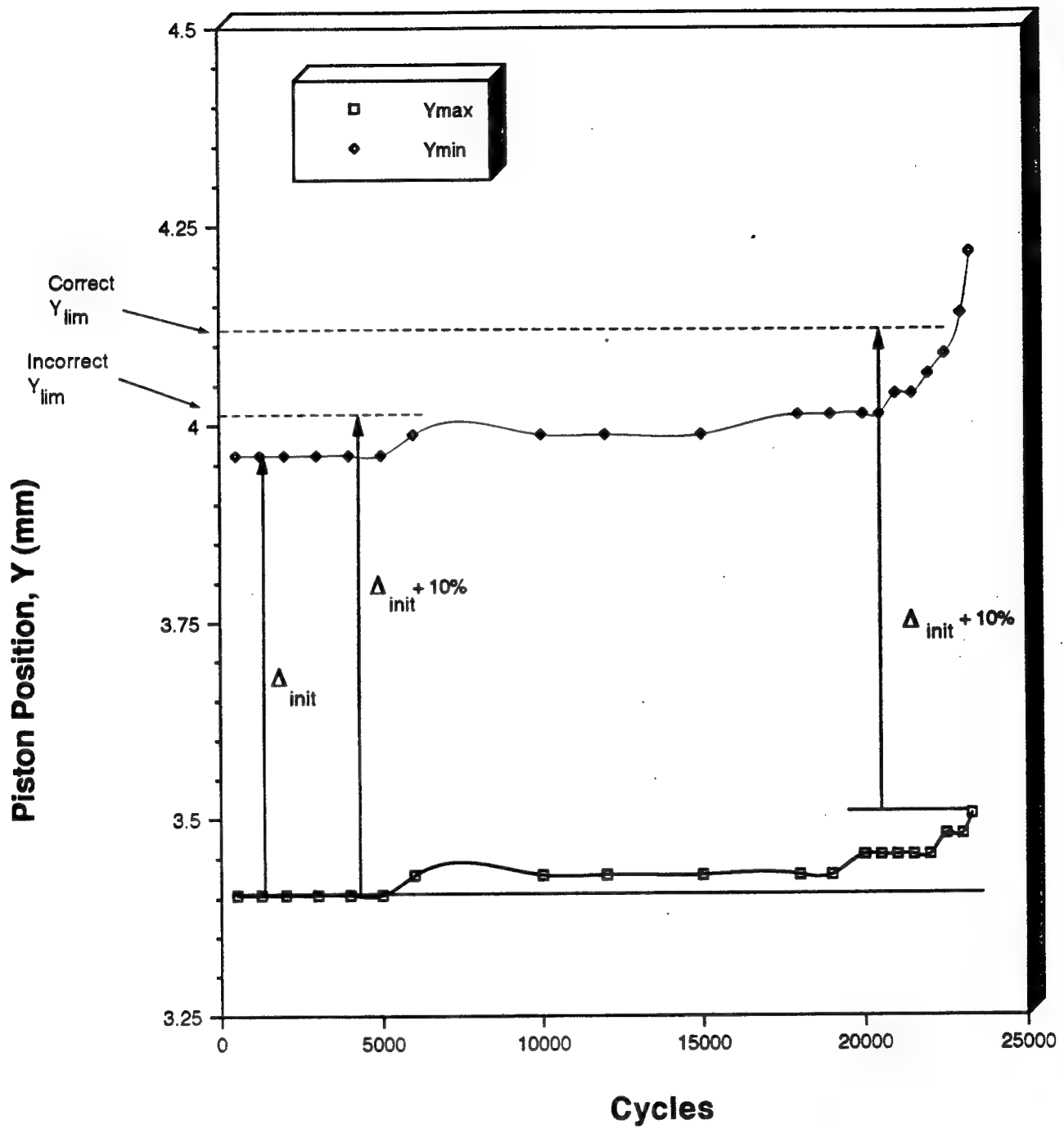


Figure 2. The change in maximum and minimum piston position during fatigue cycling. Also shown are the correct and incorrect limit set points that control the pump shut-off on the servo-hydraulic test machine.

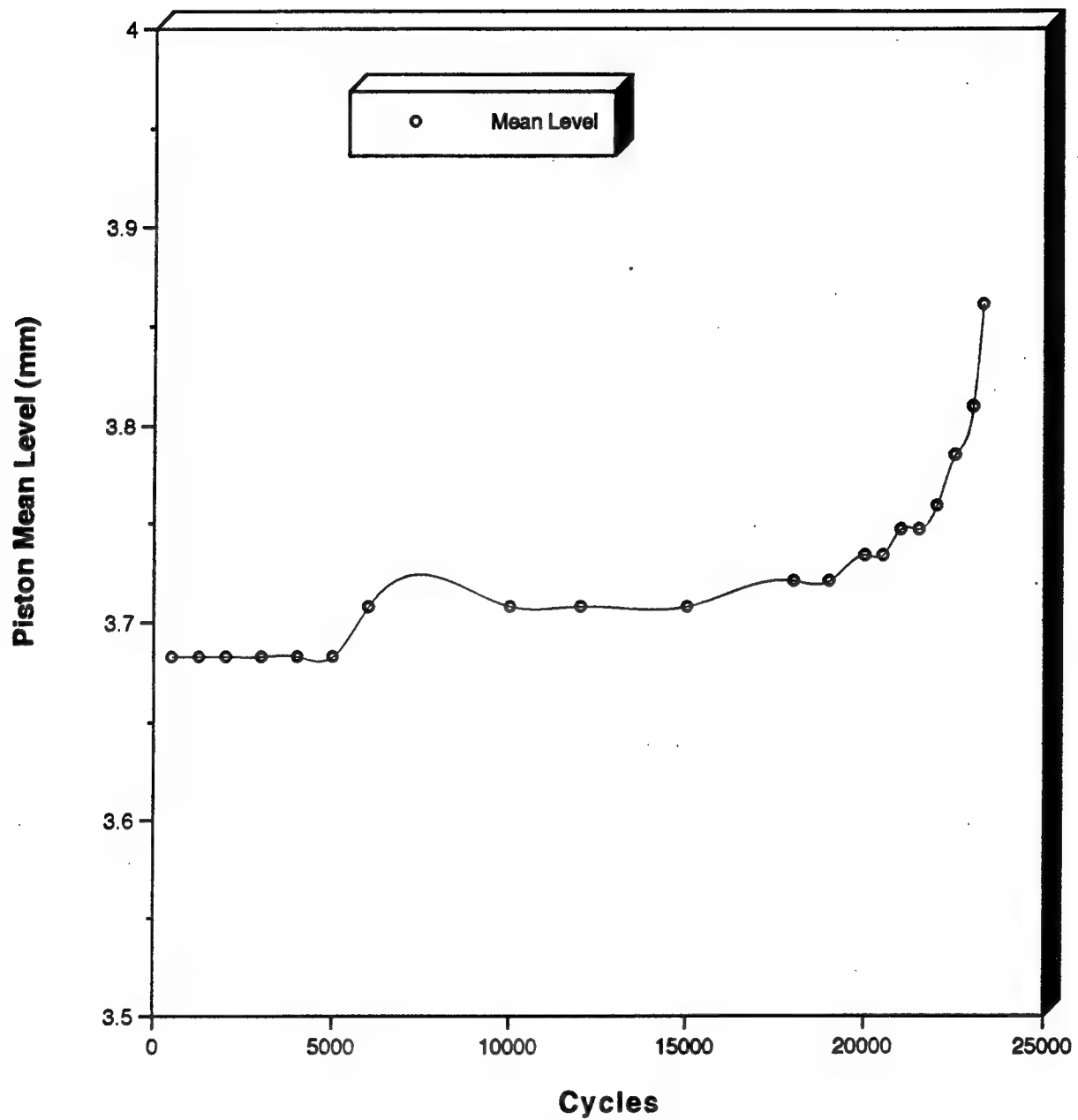


Figure 3. The change in piston mean level as a crack grows in a three-point bend specimen. (Note: Same data as Figure 2.)

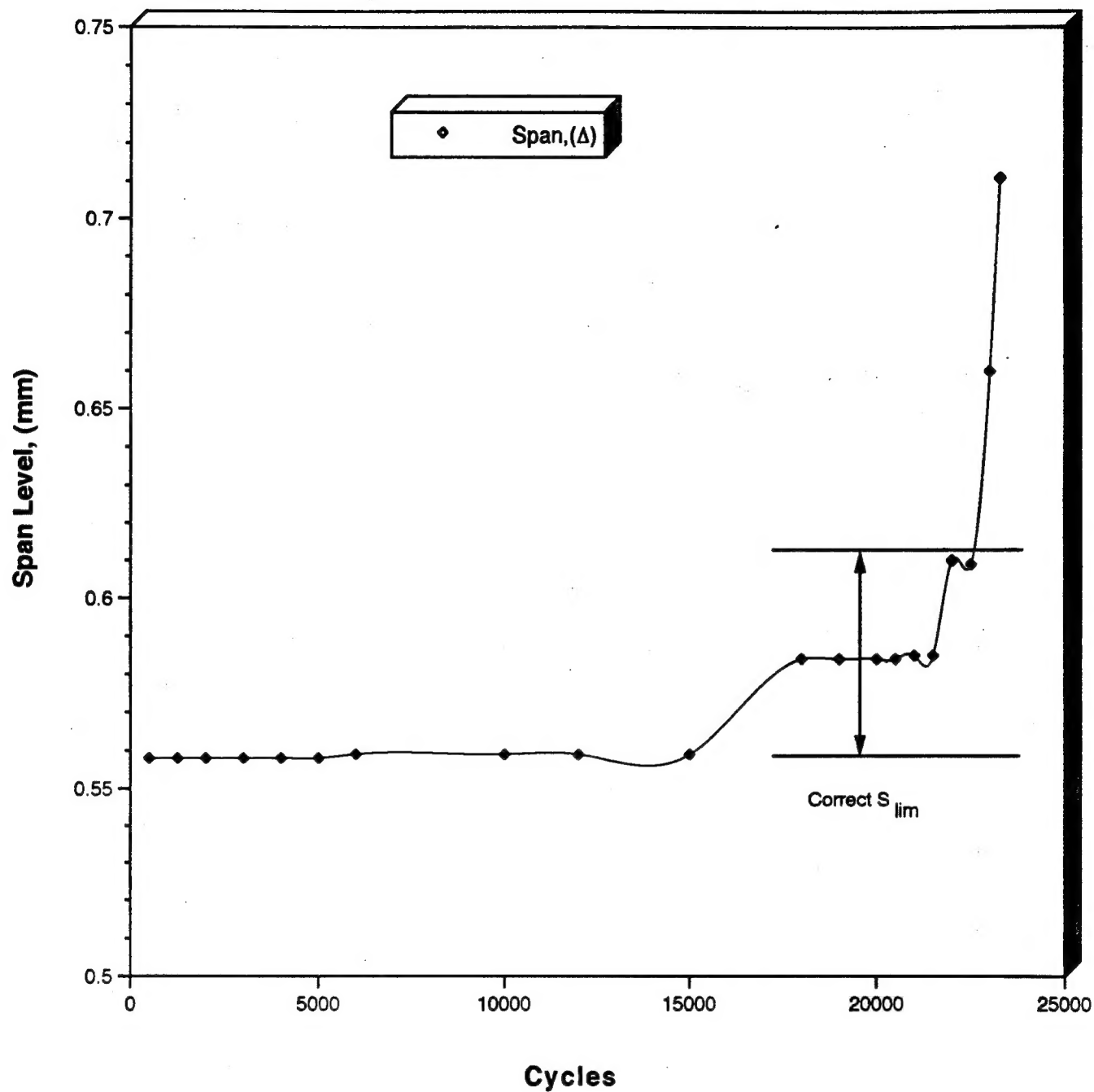


Figure 4. The change in the piston span, which is actually  $\Delta$ , as a crack grows in a three-point bend specimen. Also shown is the span limit,  $S_{lim}$ , which stops the fatigue test exactly at  $\Delta + 10$  percent.  
(Note: Same data as Figure 2.)

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